# REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-98-

0167

| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE 05 January 1998 | 3. REPORT TYPE AND DATES COVERED Final Technical (01 Jun 93 to 31 Aug 97) |
|---|---|---|

| 4. TITLE AND SUBTITLE | 5. FUNDING NUMBERS |
|---|---|
| A Non-Linear Fracture Mechanics Model for Spallation and Coupling of Nuclear Explosions Detonated in Hard Rock | F49620-93-1-0284 |

**6. AUTHOR(S)**

Charles G. Sammis

| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Southern California Department of Earth Sciences University Park Los Angeles, CA 90089-0740 | 8. PERFORMING ORGANIZATION REPORT NUMBER |
|---|---|

| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Stanley K. Dickinson AFOSR/NM 110 Duncan Avenue, Suite B115 Bolling AFB, DC 20332-0001 | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER |
|---|---|

**11. SUPPLEMENTARY NOTES**

# 19980219 118

**12a. DISTRIBUTION AVAILABILITY STATEMENT**
Approved for Public Release;
Distribution Unlimited

**DTIC QUALITY INSPECTED 2**

**13. ABSTRACT (Maximum 200 words)**

Fracture heterogeneity is known to cause non-linear effects near the source of underground explosions. Preexisting cracks nucleate new fractures which produce significant deviations from numerical computer simulations which assume a simply connected elastic continuum. Such effects were found to be important when computer models of nuclear explosions in granite failed to simulated the "pulse broadening" observed in the seismic signatures. In order to include the effects of crack growth in computer models, we have developed a micromechanical damage mechanics and incorporated it into two source models: the effective medium source model recently developed by Lane Johnson and the more traditional finite difference model used by the S-Cubed group at Maxwell Labs in San Diego. These models make testable predictions of how the waveform of radiated seismic energy depends on the depth of burial, the presence of ground water, and the size and density of preexisting fractures. They also predict the extend of damage which can be verified using extensive data sets on the density and morphology of the near-source fracture sets generated by several large chemical and nuclear explosions detonated in crystalline rock in the Soviet union. An unexpected result of these source models is the generation of significant secondary high-frequency P and S radiation by the damage could effect source detection and discrimination algorithms.

| 14. SUBJECT TERMS Damage Mechanics; Seismic Sources; Non-linear Rheology | | | 15. NUMBER OF PAGES 7 |
|---|---|---|---|
| | | | 16. PRICE CODE |

| 17. SECURITY CLASSIFICATION OF REPORT Unclassified | 18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified | 20. LIMITATION OF ABSTRACT |
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# ABSTRACT

Crystalline rock massifs in the earth's crust are heterogeneous over a wide range of scales from microcracks in grains at the micron scale to faults and joints which span many tens of kilometers. It has been observed that this fracture heterogeneity is responsible for non-linear effects near the source of underground explosions which affect seismic coupling and the resultant seismic waveform. Very near the source, preexisting cracks nucleate new fractures which can produce significant deviations from numerical computer simulations which assume a simply connected elastic continuum. Such effects were found to be important when computer models of nuclear explosions in granite failed to simulated the "pulse broadening" observed in the seismic signatures, even though the stress-strain behavior of the crystalline source rock was measured in the laboratory. Explosions in large (meter scale) samples also failed to exhibit the pulse broadening observed in the field, but were in good agreement with the computer simulation based on laboratory rheology. The solution to this apparent discrepancy was one of the early successes of our micromechanical model-based damage mechanics. It turns out that failure in compression, like failure in tension, is a scale-dependent phenomenon where strength decreases as the square root of the size of the heterogeneities which nucleate the fractures. The preexisting heterogeneity (cracks and pores) in the laboratory specimens - even the meter sized ones - were too small to nucleate the extensive fracturing which occurs in the field and which is responsible for the observed pulse broadening. Simple models for the propagation of a sinusoidal pulse through a material which exhibits the damage mechanics rheology do indeed produce significant broadening. The question is the size of the effect. Over the past several years, we have distilled the damage mechanics to a simpler form which can be incorporated in the numerical codes currently used to simulate underground explosions while still retaining the important relations to the density and scale of preexisting fractures. We have incorporated our damage mechanics into two source models: the effective medium source model recently developed by Lane Johnson and the more traditional finite difference model used by Jeff Stevens and his collaborators in the S-Cubed division of Maxwell Labs in San Diego. These models make testable predictions of how the waveform of radiated seismic energy depends on the depth of burial, the presence of ground water, and the size and density of preexisting fractures. They also predict the extend of damage which can be verified using extensive data sets on the density and morphology of the near-source fracture sets generated by several large chemical and nuclear explosions detonated in crystalline rock in the Soviet union. An intriguing implication of the damage model is that any preferred orientation of the preexisting fracture sets (fabric) may generate significant S wave energy which could effect source detection and discrimination algorithms. In our damage mechanics model, it is slip on preexisting fractures and faults which nucleates and drives new damage in crystalline rock. If the distribution of these slipping fractures are not isotropic, S wave radiation should result.

Key words:  seismic source, damage mechanics, seismic waveform, non-linear rheology

# INTRODUCTION

The overall objective of this research program has been to incorporate damage mechanics in the numerical codes used to simulate underground nuclear explosions. This work is motivated by discrepancies between theoretical and observed seismic waveforms produced by explosions in crystalline rock which have tentatively been ascribed to the extensive fracturing and granulation of the rock in the non-linear source region. It is also possible that such fracturing in an initially anisotropic medium will generate significant S wave energy.

This research is relevant to the Comprehensive Test Ban Treaty because recent advances in seismic discrimination and yield estimate of underground nuclear explosions have been based largely on high-frequency local phases such as $L_g$ and higher-mode surface waves. This shift in focus to higher frequencies has stimulated new interest in understanding the non-linear seismic coupling near the source, and in the mechanics of near-surface spallation.

While current numerical source models give an adequate representation of coupling and spall for sources buried in alluvium, significant discrepancies have been observed between model predictions and observed ground motions near explosions emplaced in hard rock like tuff and granite. These discrepancies usually involve the observation of a much broader pulse than predicted by the simulation (Rimer et al., 1987), and significantly lower displacement amplitudes (App and Brunish, 1992). App (1993) has recently identified the shear strength as the most important property of near-source rocks in shaping the seismic source function.

The problem appears to be that the numerical programs, which do a good job of modeling the compaction processes which dominate non-linear coupling in sediments, do not adequately describe the processes of crack growth and fragmentation which dominate non-linear coupling in hard rock. Crack growth is poorly modeled by current simulation programs for two reasons. First, the strength of a cracked rock is scale dependent -- strength decreases as the square root of crack length. The strength of granite measured in the laboratory is significantly larger than the strength of a granitic mass in the field simply because the length of preexisting cracks are limited by the size of the lab specimen. Hence laboratory mechanical data can not be used directly in the simulation programs. Also, the strength of the rock decreases as cracks grow during loading. A second problem has to do with the fact that, where compaction is a strengthening process which leads to a homogenization of the strain field, crack growth is a weakening process which leads to shear localization.

These same scaling problems may also explain why numerical simulations of spallation in hard rock do not seem to be as successful as those in sediments (App and Brunish, 1992). Whereas a local tensile failure criterion may work for sediments, size effects inherent in the fracture controlled tensile strength of hard rock become important.

What is needed for a more accurate numerical simulation of explosions in hard rock is a rheology which explicitly accounts for the effects of nucleation, growth, and interaction of fractures on the elasticity and strength or rock in the source region. Such rheologies are generally categorized as being "damage-mechanics" based, where "damage" is a measure of the size and density of fractures. Damage mechanics rheologies can be roughly divided into two groups: empirical formulations which are based on fracture mechanics but which have many adjustable parameters (Costin, 1983, 1985), and those which are based on a micromechanical modeling of the nucleation, growth, and interaction

of fractures growing from preexisting cracks in the rock (Ashby and Sammis, 1990). The advantage of model-based damage mechanics is that it explicitly accounts for the initial fracture spectrum in the source rock, and thus deals with the scaling problem discussed above. In Ashby and Sammis (1990), we have shown that our model gives a good description of the failure surface for a wide range of rock types with no unphysical adjustable parameters.

The source region of an underground explosion is commonly modeled as a nested series of concentric shells as illustrated in Figure 1. In the innermost "hydrodynamic regime" pressures and temperatures are sufficiently high that the rock deforms as a fluid and may be described using a PVT equation of state. Just beyond the hydrodynamic regime, is the "non-linear regime" in which the rock has shear strength but the deformation is nonlinear. This regime extends out to the "elastic radius" beyond which the deformation is linear. The objective of source models is to compute the elastic wave field at the elastic radius since this field may then be propagated to any distance using elastic wave theory.

We divide the non-linear regime into a "damage regime" in which the stresses are sufficiently high to nucleate new fractures from preexisting ones and a "crack-sliding" regime where motion on preexisting cracks produces amplitude dependent attenuation and other non-linear effects, but no new cracks are nucleated. The boundary between these two regimes is called the "damage radius" which may be computed directly from the damage mechanics expression for the nucleation of fractures (Sammis; 1990,1993).
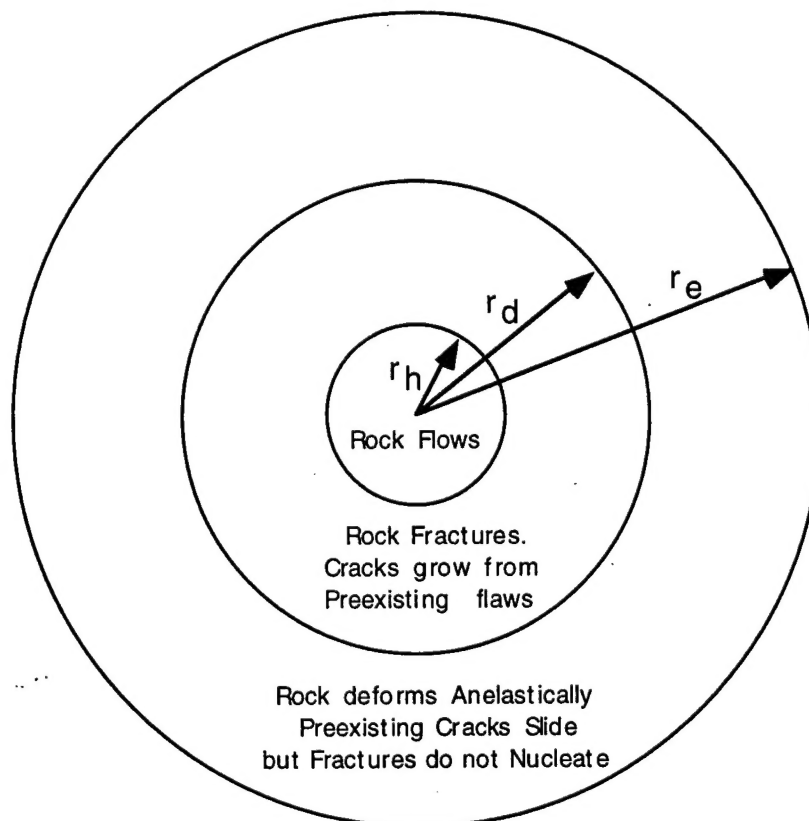


**Figure 1** Deformation regimes in the nonlinear source region of an underground explosion. For distances less than the hydrodynamic radius $r_h$ rock flows plastically. For distances between $r_h$ and the damage radius $r_d$ new fractures nucleate at and grow from preexisting fractures. For distances between $r_d$ and the elastic radius $r_e$ frictional sliding on preexisting fractures produces non-linear attenuation, but the stresses are too low to nucleate new fractures.

# RESEARCH ACCOMPLISHED

Over the past few years, we have been making significant progress in casting our model-based damage mechanics into a form which can be incorporated into the numerical codes which simulate underground explosions. We have been developing these source models in collaboration with Lane Johnson at Berkeley and, in a parallel effort, with Jeff Stevens and the group at Maxwell Labs (formerly S³) in San Diego. The two source models are quite different.

Johnson (1996) has developed an equivalent elastic source model which incorporates our damage mechanics. The equivalent elastic method calculates the stress field in the entire region surrounding an explosion. At each point in space the radial and tangential stresses are generated as a function of time and these are used to calculate whether additional crack damage has occurred. The net result is the determination of damage as a function of time and distance in the region of high stress surrounding the explosion. For the well-characterized 1 kiloton chemical explosion detonated in September 1993 and known as the Non-proliferation Experiment (NPE), Johnson calculates that the damage extends out to about 50 meters (almost 10 source radii) and that the dilatation associated with the new cracking contributes about 10% to the total dilatational moment of the explosion. The model waveforms and maximum velocity were also approximately correct. More recently, we have explored the secondary generation of high-frequence S waves by the damage process. We find that significant S wave radiation is generated if the initial damage is anisotropic. This is the case in most natural rock massifs which have a dominant fracture orientation.

However, while this approximate approach provides a very efficient method of estimating the basic characteristics of elastic waves radiated by an explosion, and for exploring the generation of secondary radiation, it does not incorporate the changes in elasticity and strength caused by the increased damage and their feedback to the source dynamics which produce the observed pulse-broadening discussed above.

In order to model the effects of changing rheology due to the increasing damage, we have to incorporate the damage mechanics into a full finite difference source code so that the changes associated with increased damage can be incorporated at each time step. In order to do this we have, with Jeff Stevens and the group at Maxwell Labs, developed an algorithm which incorporates damage mechanics into their spherically symmetric "one dimensional" code SKIPPER. We have completed preliminary calculations which indicate that the incorporation of damage alone is not sufficient to produce the observed pulse broadening. What seems to be required is additional weakening of the heavily damaged material behind the shock front. We are currently investigating whether a dynamic weakening phenormenon such as acoustic fluidization (Melosh, 1996) is supported by the modeling.

One complication which had previously delayed the implementation of damage mechanics in the numerical source codes was the fact that the effective elastic modulus during a time step is not a simple function of the damage. The elastic modulus is slightly lower if damage increases during the time interval. The calculation to find the elastic modulus which accompanies the accumulation of damage is quite complicated and not suitable for numerical implementation. We have solved this problem by introducing an empirical reduction factor to the elastic modulus and fixing its value using laboratory data. We have been assisted in this by Dr. G. Boitnott at New England Research who has generated experimental stress-strain curves for granite extending through the damage

regime up to failure. We plan to continue this collaboration to assure that the damage mechanics is firmly tied to laboratory data. Again, it should be emphasized that model-based damage mechanics is the proper framework to compare laboratory and field data since the scaling associated with crack size is built in.

The damage mechanics source model makes several testable predictions. The first is the amplitude and waveform of the seismic radiation. As mentioned above, Johnson(1996) was successful in modeling the peak velocity and waveform generated by the 1 kiloton NPE explosion using his rather crude implementation of the damage model.

A second testable prediction is the distance to which damage extends (the damage radius in Figure 1). Johnson (1966) predicted that the damage radius for the NPE explosion should extend to 50 meters (about 10 times the hydrodynamic radius). Unfortunately, the actual damage radius for this explosion was not measured. However, a new and important data set has recently become available. Dr. G. G. Kocharyan and his group in Moscow have extensive data sets on the density and morphology of the near-source fracture sets generated by several large chemical and nuclear explosions detonated in crystalline rock in the Soviet union. Based on these data, they have developed empirical relations which scale rock damage with distance and yield. For example, they find that the damage zone extends 85-140 $m/kt^{1/3}$ , slightly larger than but in approximate agreement with Johnson's (1996) estimate. If our micromechanical models are realistic, they should produce these observed scaling relations. Dr. Kocharyan's group has been working closely with Jack Murphy and the Maxwell Labs group. We are currently working with Dr. Murphy and the Russian group to collect and assess these Russian data sets in preparation for modeling .

A third testable prediction is the effect of depth of burial on the seismic radiation. For deeper events, crack growth and hence damage accumulation should be suppressed and higher frequency radiation should result.

A fourth testable prediction is the effect of ground water on the seismic radiation. To first order, ground water reduces the coefficient of friction on the sliding starter cracks by reducing the normal stress according to the effective stress law, and thus explosions below the water table produce a larger damage radius and lower frequency seismic radiation than do explosions above the water table.

Finally, a fifth testable prediction of the damage model is that any preferred orientation to the preexisting fracture sets (fabric) should generate significant S wave energy. In our damage mechanics model, it is slip on preexisting fractures and faults which nucleates and drives new damage in crystalline rock. If the distribution of these slipping fractures is not isotropic, S waves radiation should result. The Soviet group has already documented that such movement on preexisting faults and joints is so widespread that they have questioned whether elastic continuum models are appropriate, even at distances which would normally not be considered to be in the non-linear near-field regime. A quantitative estimate of the contribution of this distributed S wave source to the overall S wave field is one of our proposed tasks.

## SUMMARY AND CONCLUSIONS

To summarize, the model-based damage mechanics developed by Ashby and Sammis (1990) has been implemented in two very different models of the underground nuclear source. The simpler effective medium model (Johnson, 1996) has been used to show that the damage model predicts the correct spatial distribution of fracture damage.

More importantly, this model predicts that the secondary seismic radiation generated by the damage process makes a significant contribution to the P wave radiation and that any preferred orientation of the preexisting fracture sets in crystalline rock leads to the generation of significant S wave energy which could effect source detection and discrimination algorithms. Additional expected products of this research such as quantitative relations between the seismic radiation and the initial fracture distribution in the source rock, the depth of burial, and ground water are still in progress and should ultimately improve existing detection and discrimination algorithms by allowing them to take known geology at the source into account.

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